Liter Sized Ion Clock with 10^{-15} Stability

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Abstract— **We have recently completed a breadboard ion-clock physics package based on Hg ions shuttled between a quadrupole and a 16-pole rf trap. With this architecture we have demonstrated short-term stability ~2-3x10^{-13} at 1 second, averaging to 10^{-15} at 1 day. This development shows that H-maser quality stabilities can be produced in a small clock package, comparable in size to an ultra-stable quartz oscillator required for holding 1-2x10^{-13} at 1 second. This performance was obtained in a sealed vacuum configuration where only a getter pump was used to maintain vacuum. We have selected materials for the vacuum tube, ion trap and UV windows that will allow a 450 C tube bake-out to prepare for tube seal-off. This approach to the vacuum follows the methods used in flight vacuum tube electronics, such as flight TWTA's where tube operation lifetime and shelf life of up to 15 years is achieved. We have made a thorough study of residual gas shifts of the ion-clock frequency and a study of alternate noble gasses as a buffer gas within the sealed tube. We find that neon is more suitable than the traditional use of helium, with 2-3 times less pressure induced frequency pulling. Since neon is heavier than helium, negligible diffusion losses will occur over the operation lifetime. We have developed a modular optical system that integrates lens, mirrors, ^{202}Hg lamp and exciter, photomultiplier tube and pulse generation electronics, all into a small package that attaches to the vacuum tube, aligned with its optical ports and ion trap inside. Similarly, the reference magnetic field coil, an inner layer magnetic shield and a 40.5 GHz microwave feed with window have been incorporated into this breadboard.**

I. INTRODUCTION

A space-based clock with frequency stability better than 10^{-14} over a several day period would enable one-way deep space navigations, where Doppler data is accumulated in a down-link only fashion. Currently, deep space navigation is implemented by measuring the Doppler frequency shift of a 2-way link from a ground station to a spacecraft (s/c) and the coherent return link. Typically, these links are maintained for 7-8 hours per s/c track, requiring full use of a 34-meter antenna in the Deep Space Network (DSN) for the time the s/c is sufficiently above the horizon.

A clock with 10^{-14} or better frequency stability on board a s/c could be used to navigate to the same precision as can be done with the two-way method [1]. Additionally, when more than one s/c orbit around the same planet, they can be tracked simultaneously with one antenna. Multiple s/c tracking by a single antenna can reduce antenna usage and DSN costs.

The short-term performance in the small atomic clock described here, $10^{-13}/\sqrt{\tau}$, can steer a s/c Ultra-Stable Oscillator (USO) reaching ~ 10^{-15} in a several hours averaging time thereby supplying H-maser quality frequency stability in a much smaller package, 2-3 liters. Alternatively, this clock could be used to steer a 10^{-12} -grade quartz oscillator to exceed the typical performance of a USO beyond 100 seconds averaging and deliver 10 to 100 times improved frequency stability over that of a USO at 1-hour averaging.

Ion trapping effectively eliminates frequency pulling from wall collisions inherent to gas cell clocks. Ion shuttling allows separation of the state selection process from the clock microwave resonance process so that each can be independently optimized for its task. This separation of functions is taken for granted in atomic beam clocks but has proven to be a powerful tool with charged ions since the 'beam' of charged ions can be reversed in direction, halted, and propagated with no loss of atomic particles. Two ion trap regions are employed, a quadrupole linear trap where ions are tightly confined and optical state selection from a ^{202}Hg rf discharge lamp is carried out, and a higher pole trap where ions are more loosely confined and ~ 40.507xx GHz microwave atomic transitions are executed. The higher pole trap used for microwave clock interrogations creates less rf ion motion in the trapping fields than experienced in a quadrupole rf trap. Ion heating caused by the rf trapping fields depends on the space charge from the trapped ions, especially in a tightly confining quadrupole, and is greatly reduced within the multipole trap. Long-term variations in ion number that lead to frequency changes in clock output are greatly reduced by use of the multipole trap for 40.507 GHz ion clock-resonance interrogations. This architecture

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14. ABSTRACT
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can be implemented in a small vacuum tube where charged ions are readily transported back and forth between the two trap regions.

II. Miniaturized Ion Clock Physics Package

The liter clock ion trap is based on “ion-shuttling” between a linear-quadrupole and a linear-multipole as used in the ground clocks [2-5]. However, to meet the 1-2 liter size requirement, major re-designs in the physics package, especially the ion trap, vacuum and optical systems, are required.

A. Combined Quadrupole and Multipole Traps

The ion trap is shown below in Figure 1. The trap rods are brazed into the 3 Alumina rings on each end and at the junction between the quadrupole and 16 pole regions. The inside diameter of the electrode circle is the same as that used for the ground multipole clocks recently developed [2-5]. The purpose of the 16-pole extension is to prevent ion

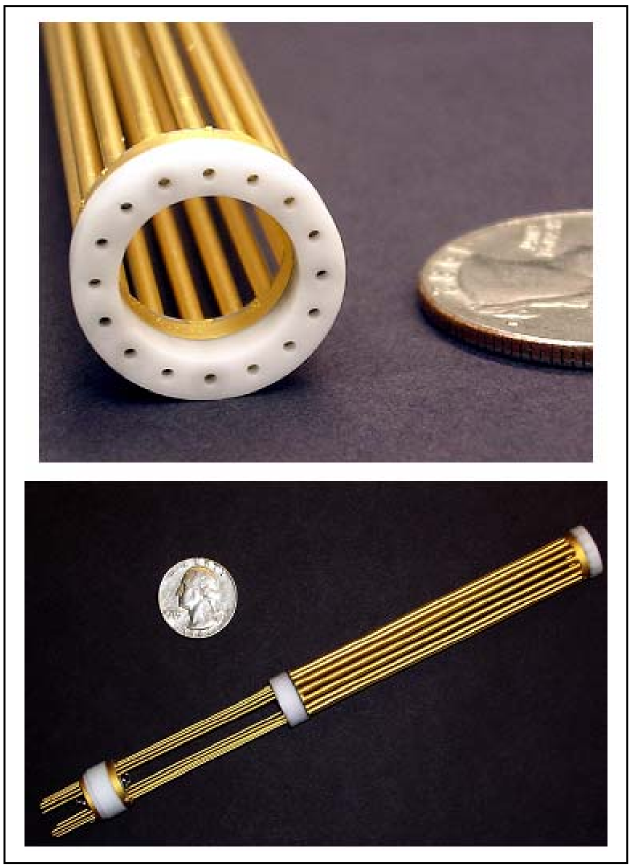

Figure 1. The quadrupole trap for ion optical pumping state selection is on the left and the 16-pole trap where the 40.5 GHz clock interrogation is made is on the right.

number variations from degrading the long-term clock stability to worse than ~ 10^{-15}. Ions experience much less micro-motion in a multipole trap, thereby reducing ion heating induced from space charge interactions in an cloud of 1-10 million ions. The remotely located 16-pole also allows ions to be moved into a region that can be better shielded from the stray magnetic fields from nearby electronics, e.g. the photomultiplier tube and lamp resonator drive electronics. The two rf trap regions will be driven at different frequencies to eliminate holes in the rf pseudo-potential near the junction [4,5]. The electrical inter-connections between rf trapping rods operated at the same rf phase is accomplished by metallic plating on the ceramics where the rods are seated. The rods are made from molybdenum (non-magnetic) so that a narrow linewidth on the 40 GHz clock transition can be achieved. The stability goal requires Q~10^{11} on this transition.

B. Optical System

Collection of UV fluorescence from the trapped Hg ions is a critical element in reaching the short-term stability 10^{-13} at 1 second. We have designed and fabricated the system shown in Figure 2, comprised of 2 UV lenses and a folding mirror. Three identical optical arms are built, one for focusing the source light from a ^{202}Hg lamp onto the trapped

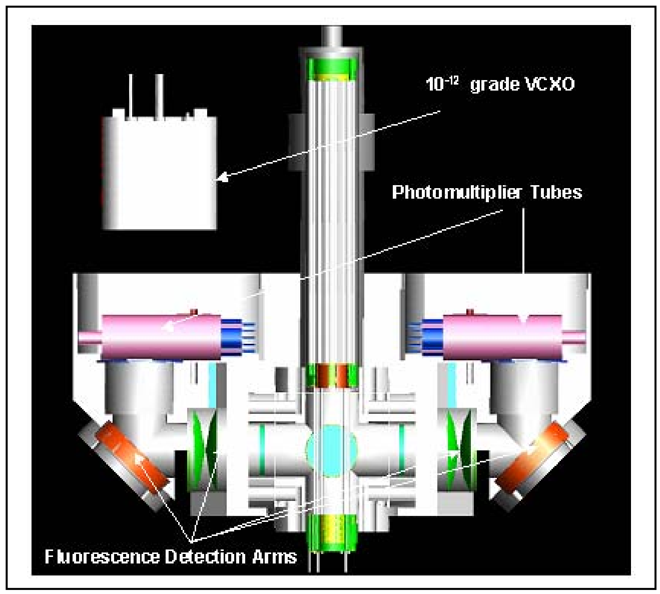

Figure 2. Optical system with vacuum tube and ion trap regions. In this view only the detection arms are visible. The input light arm is perpendicular to the page and contains the same 2 lenses and mirror.

ions and 2 more for collection of fluorescence from the ions. Since stray light limits short-term stability, it is important to eliminate the ~ 10x brighter 254 nm light from the beam. This is accomplished via bandpass filtering in the mirror dielectric coating. These mirrors are off-the-shelf items and are much less expensive than the coated spherical mirrors previously used [2-5].

The integration of this system with the ion trap assembly is also shown in Figure 2. The housing that holds the lens, mirrors, and detectors/source also holds the electronics modules used to operate the PMTs, pulse amplifier-discriminator, and discharge lamp. The integrated optical system developed here can be aligned on the bench so that the foci of the three identical optical arms fall at the same position. The optical assembly is shown in figure 3.

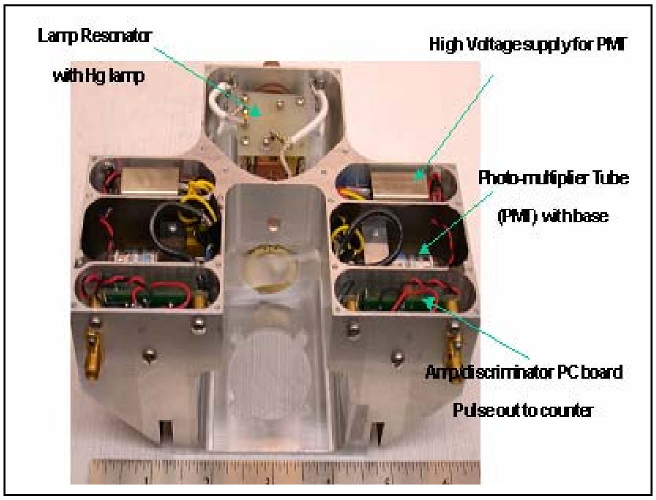

Figure 3. Breadboard Liter clock optical assembly.

C. Magnetic Configuration

The C-field direction is transverse to the axis of the multipole ion trap and is generated within a square cross-section magnetic shield and coils as shown below in figure 4. In this geometry, the WR19 waveguide is placed on the diagonal of the square layout. Two current-carrying strips on each side of the resonance region create the ~ 60

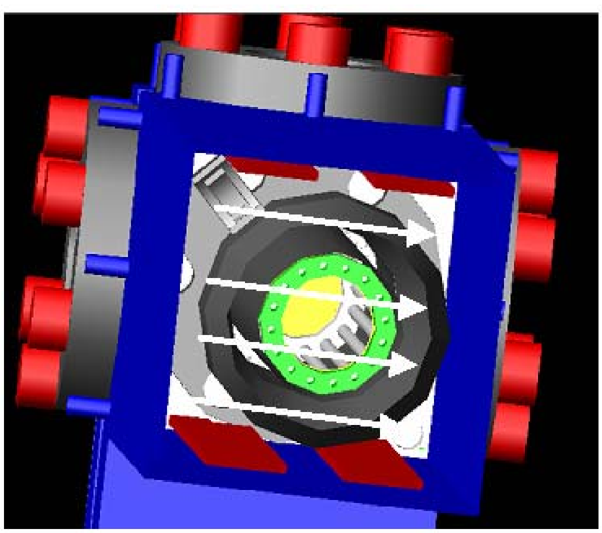

Figure 4. Cut-away view of the ion clock resonance region shows the multipole trap, the orientation of the reference C-field, and the WR19 waveguide inside the corner of the square section inner magnetic shield.

transverse magnetic field as shown. This configuration allows both clock and Zeeman transitions to be driven. That is, there are nominally equal projections of the 40.5 GHz interrogation magnetic field, parallel and perpendicular to the C-field.

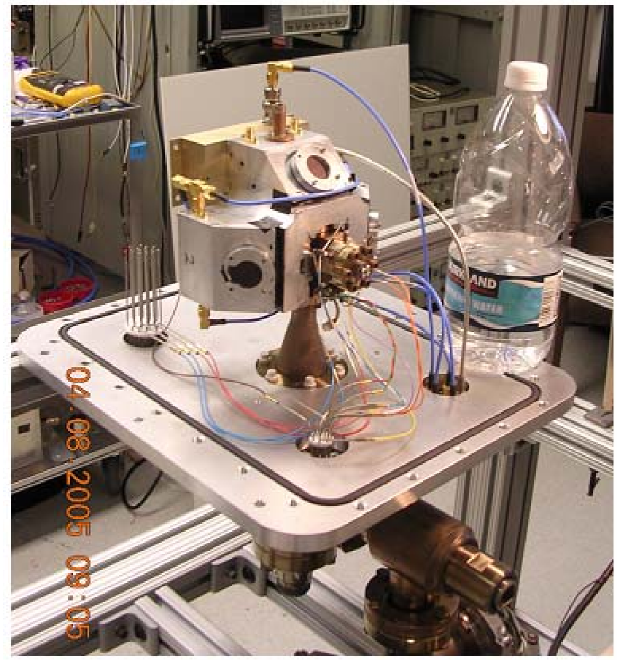

Figure 5. The breadboard liter sized ion clock physics package with connection to the UHV pump station. The aluminum base plate is for thermo-vac tests of the physics package. The liter water bottle is shown for scale.

III. Buffer Gas and Sealed Vacuum Operation

The ground clock uses a turbo-molecular pump to maintain base pressures near 10^{-9} Torr and to pump the helium buffer gas, maintained at the $\sim 10^{-5}$ Torr level. The helium buffer gas pressure is carefully regulated by a flow-thru temperature controlled quartz leak, with an ionization gauge to measure system pressure and servo the temperature of the quartz leak to maintain a given helium level.

The breadboard liter clock described here relies on getter pumping to maintain low vacuum base pressure during clock operation. These getters will not pump noble buffer gases so that a flow thru gas system is not required. Neon is used as the buffer gas in the measurements reported here since it produces a 2-3 times smaller density shift of the clock transition in Hg^+ than helium [6]. Additionally, neon diffuses less rapidly than helium.

The vacuum tube and trap parts are fabricated from materials to withstand a 450C bakeout so that the residual outgassing within the sealed tube is low enough to be pumped for many years with getter pump elements enclosed in an appendage to the tube. The metal vacuum enclosure is primarily titanium and stainless steel. UV transmitting

sapphire windows are mini-flange mounted and are bakeable to 450 C. The fully assembled clock physics vacuum elements were baked up to about 400C for a few days, but the HgO mercury source temperature was limited to ~ 260C since it will dissociate rapidly with temperature much above 300C. The system was pumped with a turbo pump during the bakeout. Following the bake, the clock was turned on and initially tested, with the pump station attached with neon flowing through a capillary leak. The neon pressure was set to ~ 10^{-5} Torr. Once good clock signals were obtained this way, the valve to the pump station was closed, isolating the physics package. For a period of ~ 8 weeks, the system was isolated with only bulk getter elements maintaining vacuum.

The lifetime for Hg ions held in the trap was very good, many thousand seconds, typically. Two layers of magnetic shielding were around the tube- the square cross-section inner set as in Fig. 4, and an outer set just outside the optics module. A typical measurement of clock stability is shown in Figure 6. In this ~3 day measurement, the microwave interrogation was via a Rabi square wave microwave pulse of 5 seconds duration. This microwave pulse was derived from a hydrogen maser.

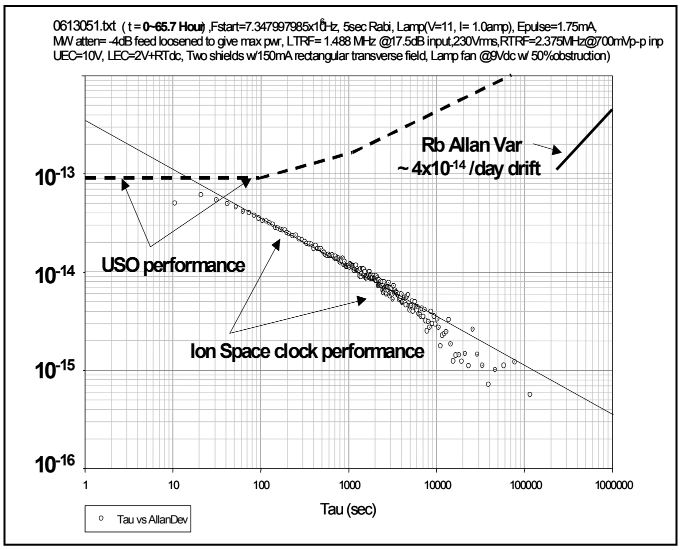

Figure 6. Allan deviation of the breadboard liter sized ion clock. This measurement was made after 6 weeks of sealed vacuum tube operation, where the ion vacuum tube was pumped with bulk getters alone.

During this measurement no additional temperature regulation was applied to the physics package beyond the laboratory room thermostat control shown in Figure 7. This shows this technology has remarkably low inherent temperature sensitivity. There are many mechanisms for frequency changes stemming from temperature, T, variations, including current changes in nearby electronics since clock frequency changes when magnetic fields from these sources are not shielded from the resonance interrogation region. Second order Doppler changes can lead to frequency pulling since this mechanism scales as $-\frac{3k_B T}{2mc^2}$, where k_B is Boltzmann's constant, m is the mass of the ^{202}Hg ion and c is the speed of light. This mechanism produces an offset frequency ~ -10^{-13} for room temperature ions. However, a 1 C ion temperature will then produce a clock frequency change ~1/300 of this value, a very modest change of only ~3×10^{-16} in clock frequency. The Doppler induced frequency pulling is probably negligible, especially if the ions are in thermal equilibrium with the buffer gas. This is another advantage of weak confinement inside a multipole ion trap. That is, within a multipole trap rf micromotion diminishes as 1/(k-1) where 2k is the number of multipole rods [4,5], in this case k=8. Additionally, the multipole confining potential (~R^{14} for the 16-pole, ref [4,5]) provides an essentially field free region through much of the interior of the trap. These mechanisms keep the ion temperature in close equilibrium with the buffer gas temperature.

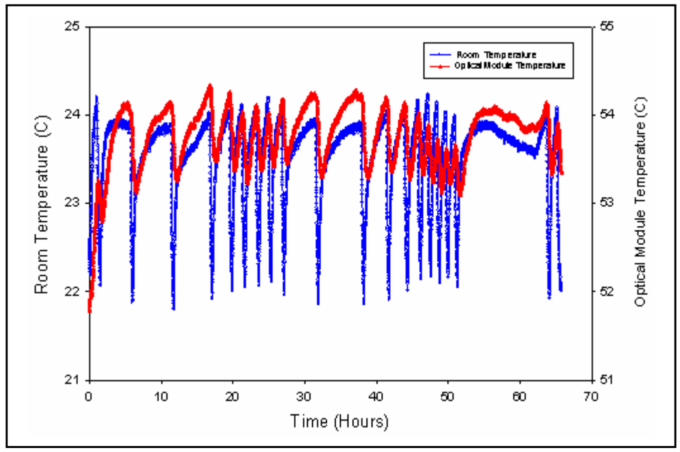

Figure 7. Temperature variation within the lab (blue trace) and on the physics package framing (red trace) during stability measurements is plotted. The clock stability under these variable temperature conditions is shown in Fig.6.

From the measured frequency stability shown in Fig 6, we can infer limits on the variation of the gases within the sealed ion tube during the ~ 3 day measurement period. We use the frequency sensitivity reported in reference [6]. We

Gas	Gas frequency pulling coefficient (Ref. 5)	Inferred maximum Gas pressure change
Neon	8.9×10^{-9}/Torr	1.2×10^{-7} Torr/day
Hydrogen	1×10^{-6}/Torr	1×10^{-9} Torr/day
Nitrogen	1.9×10^{-6}/Torr	5×10^{-10} Torr/day
Methane	3.6×10^{-5}/Torr	3×10^{-11} Torr/day

Table 1. Inferred limits on pressure changes within the sealed ion-clock tube.

assume clock frequency drift of less than 10^{-15} per day as supported by the measurements of Figure 6. The getter elements will pump Hydrogen and Nitrogen and other getterable gases, but not Neon or Methane. Mercury seems to be pumped by the getter elements since holding the HgO oven temperature at ~260C is required to maintain the clock signal.

V. SUMMARY

We have demonstrated Hg Ion clock operation in a sealed vacuum configuration and have shown frequency stability comparable to much larger Hydrogen maser frequency standards. The temperature coefficient in this configuration is extremely low, less than 10^{-15} per degree C. These advances in microwave Hg^+ clock technology will provide the basis for a ~2 liter Hg Ion space-clock with 10^{-15} long-term stability suitable for timing applications in Earth orbit and beyond, where long-term autonomous operation is required.

VI. ACKNOWLEDGEMENTS

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